Engineering Fracture Mechanics 142 (2015) 1–20

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

# Unified characterization of in-plane and out-of-plane creep constraint based on crack-tip equivalent creep strain

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ARTICLE INFO

*Article history:*
Received 13 December 2014
Received in revised form 4 May 2015
Accepted 19 May 2015
Available online 28 May 2015

*Keywords:*
In-plane constraint
Out-of-plane constraint
Equivalent creep strain
Creep crack growth rate
Finite element

ABSTRACT

In this work, the unified characterization parameter of in-plane and out-of-plane creep constraint based on crack-tip equivalent creep strain has been investigated. Based on the area surrounded by the crack-tip equivalent creep strain isoline, a unified creep constraint parameter $A_c$ has been defined. A monotonic correlation line between creep crack growth rate and the parameter $A_c$ can be formed regardless of in-plane and out-of-plane constraint and choice of the isolines, which indicates that the $A_c$ is a good unified creep constraint parameter. The parameter $A_c$ is load independent, and can characterize overall constraint levels for specimens with different in-plane and out-of-plane constraints.


## 1. Introduction

Constraint is the resistance of a structure against crack-tip plastic deformation [1]. The constraint contains in-plane and out-of-plane constraint. The in-plane constraint is directly affected by specimen dimension in the direction of growing crack, that is, the length of the un-cracked ligament, while the out-of-plane constraint is affected by the specimen dimension parallel to crack front, that is, the specimen thickness. Because the constraint can dramatically alter the material's fracture properties, it is important to develop a clear understanding of its effects on the fracture behavior of materials and structure integrity.

The characterization of constraint has been widely investigated within the elastic–plastic fracture mechanics frame, and leading to the development of two-parameter or three-parameter fracture mechanics, such as two-parameter concepts $K$–$T$ [2], $J$–$Q$ [3,4], $J$–$A_2$ [5], $J$–$T_Z$ [6–8], $J$–$h$ [9] and three-parameter concept $J$–$T_z$–$Q^T$ [10]. Most of these parameters are only used to quantify the in-plane or out-of-plane constraint separately, but not the interaction between in-plane and out-of-plane constraint and the overall level of constraints. However, in the actual engineering structures, both in-plane and out-of-plane constraint exist simultaneously. In order to describe their interaction and the overall level of constraints, a unified constraint parameter which can characterize both constraints together is required [11,12]. Mostafavi et al. [12–14] have suggested a unified constraint parameter $\varphi$ which was defined as the size of plastic region at the onset of fracture normalized by the plastic region size of a standard test:

$$\varphi = \frac{A_s}{A_{ssy}} \tag{1}$$

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http://dx.doi.org/10.1016/j.engfracmech.2015.05.044
0013-7944/

**Nomenclature**

| | |
|---|---|
| $a$ | crack length |
| $\dot{a}$ | creep crack growth rate |
| $\dot{a}_0$ | creep crack growth rate of the standard specimen |
| $A$ | constant in Norton creep model |
| $A_1$, $A_2$ | constants in 2RN creep model, and $A_2$ also is a constraint parameter |
| $A_s$ | area of the plastic region at fracture |
| $A_c$ | unified characterization parameter of in-plane and out-of-plane creep constraint |
| $A_{CEEQ}$ | area surrounded by equivalent creep strain isoline |
| $A_p$ | unified characterization parameter of in-plane and out-of-plane constraint |
| $A_{PEEQ}$ | area surrounded by equivalent plastic strain isoline |
| $A_{ref}$ | area surrounded by equivalent plastic strain isoline at fracture measured in a standard test, or the area surrounded by equivalent creep strain isoline in a standard specimen |
| $A_{ssy}$ | area of reference plastic region at fracture measured in a standard test |
| $B$ | specimen thickness |
| $B_N$ | net specimen thickness |
| $c_1$, $c_2$ | constants in stress dependent creep ductility formula |
| $C^*$ | $C^*$ integral analogous to the $J$ integral |
| $C(t)$ | $C(t)$ integral |
| $E$ | Young's modulus |
| $F$ | applied load |
| $h$ | stress triaxiality factor or factor to estimate $C^*$ in experiment using load line displacement |
| $J$ | $J$-integral |
| $K$ | stress intensity factor |
| $K_{in}$ | initial stress intensity factor |
| $L$ | characteristic length |
| $m$ | constant in stress dependent creep ductility formula |
| $n$ | stress exponent in Norton creep model |
| $n_1$, $n_2$ | stress exponents in 2RN creep model |
| $Q$ | constraint parameter |
| $r$ | distance from a crack tip |
| $R$ | creep constraint parameter |
| $R^*$ | load-independent creep constraint parameter |
| $T$ | $T$-stress constraint parameter |
| $Tz$ | out-of-plane constraint parameter |
| $t$ | creep time |
| $t_{red}$ | creep redistribution time |
| $\dot{V}_C$ | creep load line displacement rate |
| $\dot{V}_t$ | total load line displacement rate |
| $W$ | specimen width |
| $\theta$ | polar coordinate at the crack tip |
| $\dot{\varepsilon}_0$ | creep strain rate at normalizing stress |
| $\dot{\varepsilon}_c$ | creep strain rate |
| $\varepsilon^* f$ | multiaxial creep ductility |
| $\varepsilon_f$ | uniaxial creep ductility |
| $\varepsilon_{f1}$ | lower shelf creep ductility |
| $\varepsilon_{f2}$ | upper shelf creep ductility |
| $\varepsilon_c$ | equivalent creep strain |
| $\varepsilon_p$ | equivalent plastic strain |
| $\varphi$ | a unified constraint parameter defined by plastic region area |
| $\sigma_0$ | normalizing stress |
| $\sigma_{22}$ | opening stress |
| $\sigma_{22,CT}$ | opening stress of CT specimen under plane strain |
| $\Delta\sigma$ | opening stress difference |
| $\sigma_e$ | von Mises equivalent stress |
| $\sigma_m$ | mean normal stress |
| $\sigma_y$ | yield stress |
| $\omega$ | damage parameter |
| $\dot{\omega}$ | damage rate |
| $\eta$ | factor to estimate $C^*$ in experiment using load line displacement |